Chapter 12
Bio-inspired, Flexible Structures and Materials

J. Lienhard, S. Schleicher and J. Knippers

Abstract This chapter discusses the potential of biomimetics in formfinding and the development of structural systems based on constant or reversible elastic deformation. The existence of high strength elastic materials are the preconditions for the technical realisation of such elastic structures. Therefore, this chapter will start by introducing elastic building materials and biomimetic abstraction techniques individually before bringing the two together by presenting case studies which successfully combined both aspects.

12.1 Introduction

The inseparable combination of form, material, and function is a criterion, which is typically more appropriate to describe natural than technical system. However, due to the increasing availability of high-performing materials on the one hand and the rising computational power of our simulation and planning tools on the other, it is now possible to explore structures whose form arise from their material behaviour instead of being the result of pre-defined typologies. The research presented in this chapter aims to explore exactly this relationship between form and material behaviour on the basis of biological principles and will discuss possible functions for architectural applications. Therefore, examples of static and kinetic structures whose form and adaptability are based on elastic deformation will be examined closely. From this point onwards, these systems will be referred to as 'bending-active' and 'elastic-kinetic' structures (Knippers et al. 2011a, b).

Bending-active structures are structural systems that include curved beam or shell elements, which base their geometry on the elastic deformation from an

J. Lienhard · S. Schleicher · J. Knippers (✉)
Institute of Building Structures and Structural Design (Itke),
University of Stuttgart, Stuttgart, Germany
e-mail: j.knippers@itke.uni-stuttgart.de

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initially straight or planar configuration. The category of elastic-kinetic structures takes this form-defining approach one step further by considering that the deformation process can also be reversible thus allowing the creation of adaptive systems and compliant mechanisms (Lienhard et al. 2010; Schleicher et al. 2011).

An initial review by Lienhard et al. (2013a, b) on bending-active structures has shown how these systems face two major challenges in the design process: Firstly, since bending-active structures are not based on known typologies, the central question is about the form and functional inspiration. Secondly, there is the difficulty of predicting the system's geometrical shape or structural performance without immediately consulting advanced digital simulations or physical tests.

Recent studies suggest that biomimetic abstraction processes can provide helpful scientific methods that may be used for the design of elastic systems entirely born out of a process based on material behaviour rather than typology based model thinking. (Knippers and Speck 2012; Knippers 2013). This trend is also supported by computational developments, which enable the simulation of nonlinear behaviour in large elastic deformations. In fact, today, the engineering of a structure is increasingly becoming an essential part in modern design processes and is no longer a downstream proof calculation that comes into play when the decisions about shape and form have already been made.

A constructional design approach based on flexibility rather than on stiff members and movable joints however has not yet established itself. In terms of today's building industry there is uncharted ground, in which experience and expertise is lacking and role models are scarce. Interestingly, however, soft and flexible structures are rampant in Nature and indicate the promising potential of this construction principle. It is therefore reasonable to combine research on flexible structures and materials with the topic of biomimetics; with the goal of understanding flexible structures in biology and to transferring, scale-up, and implement their underlying principles into bio-inspired technical devices and structures.

So far, however, most bio-inspired technical structures consider applications either purely theoretically and/or include very simple models on laboratory scale (Marder and Papanicolaou 2006; Kobayashi et al. 2000; Liang and Mahadevan 2009; de Focatiis and Guest 2002; Jenkins 2005). Even the most well known elastic kinetic structures, namely deployable space structures like foldable solar panels and retractable satellite antennas (Miura 1993; Furuya and Satou 2008), which are often discussed in relation to biologically inspired folding and unfolding techniques, are inspired by traditional Japanese folding techniques (e.g. Origami) rather than actual studies of flexible structures in plants and animals.

Only recently, some projects like the patented Fin Ray Effect® (Patent: Leif Kniese 2012) or the Flectofin® (Patent: Knippers et al. 2011a, b) have attracted attention and open up the potential for a successful implementation of bio-inspired flexible structures and materials.

12.2 The Design Potential of Elastic Construction Materials

A fundamental pre-requisite in the designing of bending-active structures is the characteristics of particular building materials which provide a beneficial ratio of high strength and low bending stiffness. Traditional building materials such as timber, for example, offer a suitable elastic range. Fibre Reinforced Polymers (FRP) embody an even greater potential for lightweight bending-active structures due to their low density and high breaking strain. Constant improvements in the development and composition of custom-made, high-performing FRPs suggest that there will be even more materials to choose from in the future.

12.2.1 Material Overview

Among the materials we can consider working with in building and construction, there is a wide range of strength, stiffness, and densities available. Some materials are more suitable for bending-active structures than others. Comparing steel with rubber, for example, one may expect that rubber is the more appropriate choice due to its compliant nature. However, the low tensile strength of rubber makes it unsuitable for structural applications. The much stronger steal, in comparison, offers high tensile strength but is also comparably stiff. As a result neither of these two materials can really be considered as a favorable option for the design of bending-active structures.

In the screening process for the most suitable materials it is therefore important not to focus on one material characteristic only. Instead, the combination of material properties is much more significant. Choosing the right material parameters necessitates an understanding of the mechanical relationships in large elastic bending deformations. From the Euler-Bernoulli law we know that the bending curvature is proportional to the bending moment M (1) (Fertis 2006, p. 9). For flat sections or plates the width has no influence on the bending stress which can therefore be expressed proportional to the thickness t and curvature $1/r$ as shown in (2). This leads to the formulation of the minimal bending radius (3) which we can use to analyse different building materials for their potential use in bending-active structures. The most important variables to set into relation here are the Young's Modulus E and permissible bending stress $\sigma_{M,Rk}$. It can thus be concluded that an optimal material for bending-active structures would ideally combine low stiffness and high tensile strength.

$$\frac{1}{r(x_0)} = \frac{M(x_0)}{E \cdot I} \tag{12.1}$$

$$\sigma_M = \frac{E \cdot I}{r \cdot w} = \frac{E \cdot t}{2 \cdot r} \tag{12.2}$$

$$r_{\min} = \frac{E \cdot t}{2 \cdot \sigma_{M,Rk}} \quad (3)$$

Previous work by Ashby has provided very helpful tools in the selection of adequate materials for a given design task (Ashby 2005). The 'Ashby diagrams' open up a property-space by comparing multiple material classes to each other as well as identifying the property range within the individual classes. Providing design guidelines to define specific 'search regions' additionally facilitates the practical use of these diagrams. Figure 12.1 follows Ashby's approach and lists a selection of common building materials. Here, the materials are plotted on a graph with logarithmic scale and are brought into context based on their ratio of flexural strength to stiffness. The range of the axis is chosen to include the material classes investigated. Focusing on the context of building structures, the values in Table 12.1 are taken from the Eurocodes DIN EN 1993–1995 and 1999, DIN 1052:2004–08, and DIN 17221, as well as from Knippers et al. (2011a, b, p. 77) and Gas et al. (1985).

Based on this diagram, adequate materials for static bending-active structures should offer a ratio of $\sigma_{M,Rk}/E > 2.5$ (with $\sigma_{M,Rk}$ [MPa] and E [GPa]). When it comes to elastic-kinetic structures and large-scale compliant mechanisms, the additional requirements for fatigue control further limit the permissible permanent elastic stress; therefore, a ratio of $\sigma_{M,Rk}/E > 10$ is needed. This is indicated by the design guideline with the inclination $\sigma_{M,Rk}/E$. Moreover, the diagram shows clearly that Fibre-Reinforced Polymers (FRP) and certain types of timber and high strength metals are particularly appropriate materials for the use in bending-active structures. When it comes to elastic-kinetic structures and large-scale compliant mechanisms, FRPs mostly fulfil these requirements.

In addition to this short overview, it is critical to consider the material's long-term behaviour. For static bending-active structures, this means paying particular attention to time-dependent deformation (creep). The effects differ in the various materials and are significantly higher in timber than in FRP, for example. The creeping of a material needs to be considered because it can lower the pre-stress in the structure, which dependent on the design of the structure can be more or less relevant and may negatively affect the system's integrity. If the pre-stress is not playing a decisive role for the structure's stiffness, materials such as timber may be chosen. Regarding elastic-kinetic structures, the most important long-term behaviour that needs to be checked is a material's fatigue behaviour. Only if a chosen material has a sufficient fatigue life it can be guaranteed that the compliant mechanism can undergo high and cyclical loading. For the designer, however, it is difficult to assess if the mechanism can perform according to the prescribed functions because the motion of its deflecting members is limited by their strength, which is a property that is not easily readable from the outside. Therefore, precise knowledge of the material properties and the desired motion range is required when designing an elastic-kinetic structure.

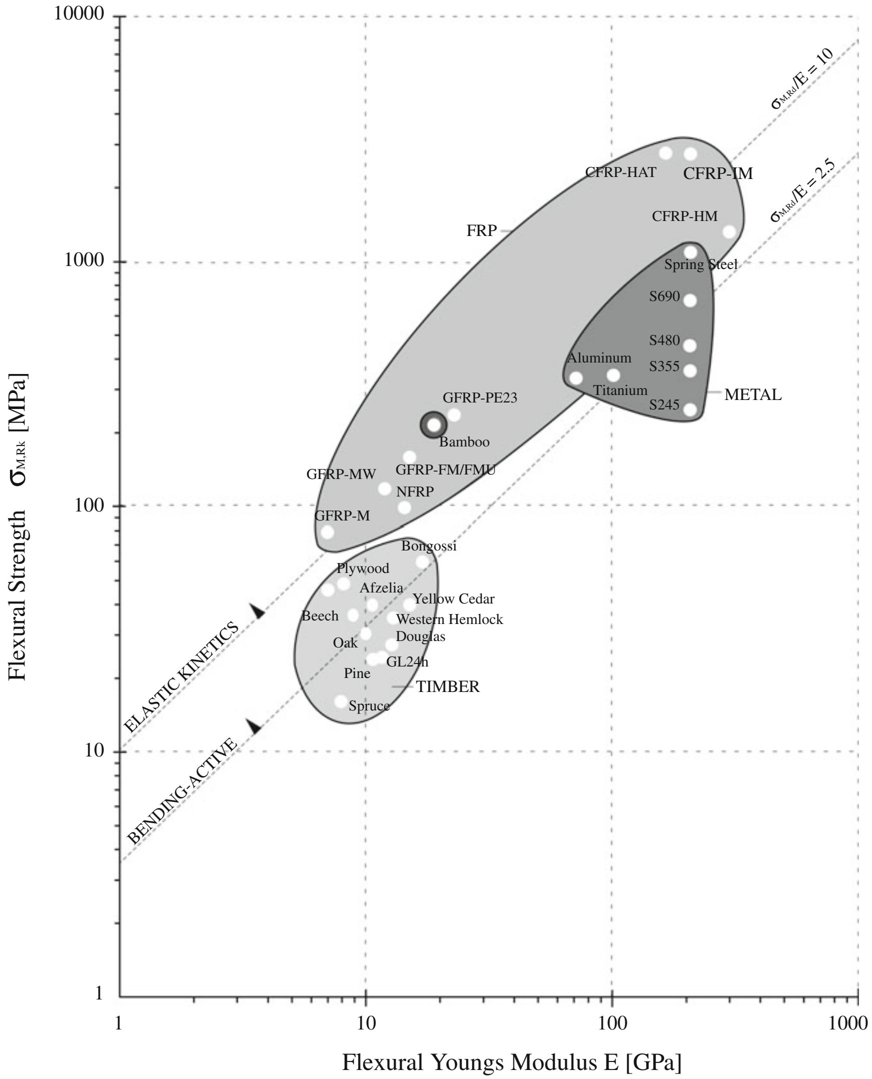

Fig. 12.1 Common building materials with ratio of strength $\sigma_{M,Rk}$ (MPa) to stiffness E (GPa). Adapted from Lienhard et al. (Lienhard et al. 2013a, b)

12.2.2 The Potential of Using Elastic Materials for Compliant Mechanisms

The reason why elastic materials are growing ever more popular, in particular for use in compliant mechanisms, is due to the various benefits that this construction principle possesses over conventional mechanics: By gaining motion through the

Table 12.1 Common building materials with ratio of strength $\sigma_{M,Rk}$ (MPa) to stiffness E (GPa)

	Flexural strength [MPa]	Flexural youngs modulus [GPa]	Ratio
Metals			
S245	245	210	1.17
S355	355	210	1.69
S450	450	210	2.14
S690	690	210	3.29
Spring steel	1100	210	5.24
Titanium	340	102	3.33
Aluminum	330	70	4.71
Timber			
Spruce	16	8	2
Pine	24	11	2.18
Douglas	30	12	2.5
Western hemlock	35	13	2.69
Yellow cedar	40	15	2.67
Oak	30	10	3
Beech	35	10	3.5
Afzelia	40	11	3.64
Bongossi	60	17	3.53
GL24 h	24	11.6	2.07
GL28 h	28	12.6	2.22
GL32 h	32	13.7	2.34
GL36 h	36	14.7	2.45
Birch plywood (6.4 mm)	50.9	12.737	4
Brich plywood (18 mm)	40.2	10.048	4
Combi-plywood (6.4 mm)	50.8	12.69	4
Combi-plywood (18 mm)	35.8	8.95	4
Softwood plywood (6.4 mm)	29.1	9.462	3.08
Softwood plywood (18 mm)	23	7.464	3.08
Bamboo	213	19.129	11.13
FRP			
Type			
CRFP-HAT	2800	165	16.97
CRFP-IM	2800	210	13.33
CRFP-HM	1350	300	4.5

(continued)

Table 12.1 (continued)

	Flexural strength [MPa]	Flexural youngs modulus [GPa]	Ratio
P E 23	300	23	13.04
GRFP-M	80	7	11.43
GRFP-MW	120	12	10
GRFP-FM/FMU	160	15	10.67
NRFP	101	14.38	7.02

flexibility of the construction, rather than linking multiple rigid parts together, one may cause a dramatic reduction in the total number of parts required to accomplish a specific mechanical task. Reducing the amount of parts may decrease assembly time and simplify manufacturing processes, which in turn may result in significant cost reduction.

Another important benefit is that compliant mechanisms often show an increased performance regarding reliability. This is due to the fact that they have few or no hinges, comparable to conventional revolute or sliding joints. Thus, the wear in these structures and the need for lubrication is very low. These are valuable characteristics, especially for applications where mechanisms are either difficult to access or operating in harsh environments, in which conventional joints would rust and require significant maintenance.

Furthermore, one of the main advantages of compliant mechanisms is their capacity to store energy in their deflected flexible members. If a compliant mechanism is based on material with little creeping behaviour, it can store strain energy over a longer time period and release it at wish at a later stage, or use it to reset the mechanism to its original state again. But beyond that, it is also possible to fine-tune the force-deflection relationships in the flexible structure to correlate energy and motion and vice versa. The transmission ratio therein can be tailored to suit specific functional needs with targeted amplification effects. For a given energy input the mechanical response of compliant mechanisms can be customised to achieve, for instance, either a maximum displacement (displacement multiplication), or a maximum resulting force (force multiplication).

12.3 Biomimetic Approach

In the last decade, using nature as an inspirational source to solve technical problems has become scientifically recognised. Through the evolutionary pressure of natural selection on organisms to survive under particular boundary conditions, highly-adapted systems have developed. In order to use such systems as role models for technical applications a ‘top-down approach’ can be used to solve technical problems by formulating a concise technical question which evolution may have already developed an answer for. Elastic-kinetic structures may be derived, for example, from flexible deployable systems found in nature. These can be observed especially in movements of plants or plant organs. Of particular interest are non-autonomous plant movements which usually show a clear interrelation of form, actuation, and kinetics. In the following section two strategies are presented which may be used to extract principles from nature for bending-active structures and compliant mechanisms.

12.3.1 Direct Methods in the Context of Compliant Mechanisms

In general, the work with biological role models can be initiated by two different biomimetic process sequences, which, in the further development of an iterative design process, are often mixed. The basic processes are:

> Bottom-up = biology push: In this approach new biomimetic research projects for technical implementation are born from new and promising results of fundamental biological research. The first step of the process (…) is to analyse the biomechanics and functional morphology of a biological system. In the next step quantitative analysis leads to a principal and detailed understanding of the biological structures, shapes and functions. On the abstraction level, which follows, separation of the principles discovered in the biological model takes place. Abstraction often proves to be one of the most important as well as most difficult steps in a biomimetic projects. (Speck and Speck 2008, p. 6)

> Top-down = technology pull: A biomimetic project following the top-down process typically starts with the work of an engineer. In this approach biomimetic innovations and improvements are sought for in already existing technical products. These products might either be in a final state of industrial development, or are often already successfully established on the market. For a successful top-down process well founded expertise is required from company representatives (engineers) as well as from fundamental researchers (biologists), and also readiness to talk with the parties on both sides. The improvement or further development of an existing product stands in the centre of the cooperation during a top-down process. (Speck and Speck 2008, p. 7)

So, the top down approach begins by defining the question. For instance, the overriding question in the development of compliant mechanisms is the optimisation of adaptability and energy efficiency of kinetic systems as well as the lowering of their weight and maintenance costs.

When aiming for biomimetic solutions, a proven first step can be a screening of natural concept generators with a high potential for translation into technical applications. Usually, the most evolved and robust answers can be found in organisms which developed under high selective pressure (Reith et al. 2007). Plant movements, for example, are particularly adequate for translation into kinetic architectural structures. Unlike animal locomotion, which is usually laid out for a variety of complex movements, the actuation systems of plants are evolutionary optimised to perform a single type of movement (Sitte et al. 1991). Furthermore, the structures of the mostly sessile plants are often adapted for similar boundary conditions such as those which affect the design of the architectural structures.

Once the objective is set the screening process can be carried out. In the particular cases analysed in this chapter the biological role models which best meet the requirements and demonstrate possible solutions for potential technical implementation are gathered.

In order to narrow down the search parameters some screening criteria should be further defined. For example, in the search for compliant mechanisms the focus was placed on reversible elastic or visco-elastic deformations in plants. Plant movements are based on many different motion principles, some of which only occur in highly specialised plant groups like trapping mechanisms in carnivorous plants or pollination mechanisms in the flowers of a specific plant family.

These optimised biological mechanical systems are promising concept generators for the design of elastic structures in architecture since they often combine sensors and actuators within one mechanical system.

For the further analysis of the selected specimens it is helpful to build up a phenomenological understanding of the underlying physical principles that are involved in the observed mechanisms. Therefore, it can be a good approach to apply even more stringent selection criteria in order to find examples with the greatest potential regarding cost efficiency, energy and material solutions. Again, in the context of compliant mechanisms, a precisely defined selection criterion can be the prioritisation of research for systems with large bending radii, small actuation and beneficial energy transmission, or an alternative freedom of movement that can usually not be found in conventional rigid body mechanics.

The final step in this process is the abstraction of the role model into a bio-inspired mechanism. This is probably the most difficult step in the transfer process since it requires both scientific rigor as well as a high level of creativity. In order to unveil the basic mechanical principles involved, one must study the functional-morphological relationships in the biological role model very systematically. The process of reduction and dissection are very helpful examples. Here, the functionality of a mechanism in a specimen is tested by progressively cutting off all the elements that seem to be unrelated to the mechanism. By following this approach, one can narrow down the constituent parts that play a key role in the mechanism. This is of particular importance because the knowledge about the basic building blocks that are needed for a mechanism opens the door for their creative use. Then, one can start to modify these building blocks, reconfigure them, or fine-tune and optimise them in order to address various tasks.

This insight significantly broadens the design freedom and allows for concepts beyond the direct mimicry of the natural system. A reinterpreting of the mechanical principle and the development of novel kinetic systems can be followed through, with the help of physical and digital models, for example. Upon further analysis of the abstracted mechanical principle, the working process may be opened up for reconfigurations and adaptations to meet the boundary conditions given by a technical implementation.

The technical implementation in the form of a reduced scale or full scale prototype lies not at the end, but rather amidst an iterative design process in which feedback from real construction can reach as far back as fostering the understanding of the biological role model.

12.3.2 Indirect Biomimetic Approach

While the approach described above concentrates on singular phenomena and their direct technical implementation, biomimetics can also support the design process when looking at natural design and construction principles from a more general perspective. Knippers and Speck (2012) highlight a number of design principles that lead to structures with multiple network functions based on a multi-layered, finely tuned and differentiated combination of basic components. Additionally, Gruber (2011) selects some design strategies found in natural organisms that may be of relevance for architectural constructions. From these sources, a list of natural principles can be summarised that may be particularly applicable for the integrated design approach pursued with bending-active structures and compliant mechanisms. (Based on Knippers and Speck (2012) and Gruber (2011):

- *Heterogeneity*: Natural constructions are characterised by geometric differentiation.
- *Anisotropy*: Many natural constructions consist of fibre reinforced composite materials.
- *Hierarchy*: Biological structures are characterised by a multilevel hierarchical structure.
- *Multifunctionality*: In botany, fibres simultaneously serve mechanical and diverse physiological functions.
- *Adaptability*: Many short- and long term adaptations are known from natural systems that adapt to their environment.

It should be noted at this point, however, that while all these principles already provide a helpful guidance and inspiration for the design of bending-active structures and compliant mechanisms, this list makes no claim of completeness. A detailed explanaition of these principles is given in VDI 6226 (2014). In fact, it could be easily expanded by many other key aspects (e.g. redundancy, self-healing), in order to address specific levels of perspective or to reach paramount objectives such as closed material loops, effective energy conversion or sparing use of resources.

Nevertheless, this first overview of natural principles already provides a useful starting point. With focus on bending-active structures in the context of lightweight structures, for example, it can be shown how these natural principles may also be linked to the threefold engineering classification of lightweight structures (Wiedenmann 1989):

- *Light Materials*: Materials of low density combined with high mechanical strength
- *Light Structures*: Following the flow of forces on minimal paths
- *Light Systems*: Integration of multiple functions into a single element

In Table 12.2 the engineering classifications of lightweight structure and natural design principals are compared, to identify natural construction principles which may be consulted to find new engineering solutions for lightweight structures. Such a comparison may be used as a starting point in architectural design and engineering when aiming to include biomimetic principles in the working process.

12.4 Case Study Projects

The following two case study projects exemplify a typical direct top-down approach (Flectofin®) and an indirect approach (M1).

12.4.1 Flectofin®

The first case study followed a direct biomimetic approach. In this project, the Bird-Of-Paradise flower, also known as *Strelitzia reginae* (Fig. 12.2), was chosen as a role model because it features a sophisticated externally actuated pollination mechanism. The motion is part of an elastic and reversible valvular pollination mechanism, which is driven by the direct application of an external force. This mechanism was intensively studied in order to reveal the underlying principles that are responsible for the plant's mechanical performance. The plant's distinct form-structure-function relationship was then further abstracted and inspired the development of an elastic flapping mechanism called Flectofin®. Exemplarily, it is used for the conceptualisation of an adaptive façade shading system (Fig. 12.8), in which the fins allow for opening angles ranging from −90° to +90°.

12.4.1.1 Biomimetic Approach

As an adjustment to its relatively large and heavy pollinators (mainly birds), *S. reginae* has developed a protruding perch of two adnate petals that act as a landing platform. When a bird lands on this structure to reach for nectar, its weight causes the perch to bend downwards, as shown in Fig. 12.2. This initial deformation triggers a secondary sideways flapping of two thick petal wings. As a result, the previously enclosed stamens are exposed and pollen is transferred to the bird's feet. When the bird flies away, the open perch resets to a protective closed state

Table 12.2 Comparison of engineering and natural design principles

Engineering principles	Natural principles
Light materials	Anisotropy
Light structures	Heterogeneity
	Hierarchy
Light systems	Multifunctionality
	Adaptability

again and the bird may transport the pollen to another Strelitzia flower where pollination takes place.

The flapping mechanism of the *S. reginae* is particularly suitable for a technological transfer because it can be triggered at any time by applying an external mechanical force at a specific location of the structure. When loaded this way it shows what is defined in engineering terms as a distinct tipping failure. This phenomenon permits a series of experiments with which the mechanism can be investigated precisely in order to learn more about its functions.

In this case the abstraction can take place via a reduction principle. While doing so, parts of the plant that may not have anything to do with the basic kinematics are gradually cut away. Hereby it becomes clear, that only individual halves of the leaves with directly connected reinforcing strip are responsible for the flapping mechanism (Fig. 12.3). Such a system can easily be imitated and simulated with physical models (Fig. 12.4).

This biological principle unveils an elastic flapping mechanism which is transferrable to technical fields of application. In contrast to common kinetic structures which work on the basis of locally arranged hinged, jointed and angular connections, the biomimetic approach works on the basis of pliability of large surfaces. This enables a wide range of adaptation and the wear of material at the joints and hinges can be avoided. This principle represents a paradigmatic shift in civil and structural engineering wherever it was previously recommended to avoid any form of structural failure. The actual mechanism behind this movement is known as lateral torsional buckling in engineering, a so-called ‘failure mode’ that engineers generally try to avoid by sizing structural members to adequate stiffness. The physical model in Fig. 12.4 shows the effect of lateral torsional buckling in a constellation as can be found in the plant’s mechanism. In the *Strelitzia*, however, this failure mode has no negative connotation but simply utilises as fundamental motion principle for a highly effective compliant mechanism. In fact, *S. reginae* cleverly exploits the potential of an unsymmetrical bending motion as an integrative part within a reversible deformable structure with multiple deflected equilibrium positions.

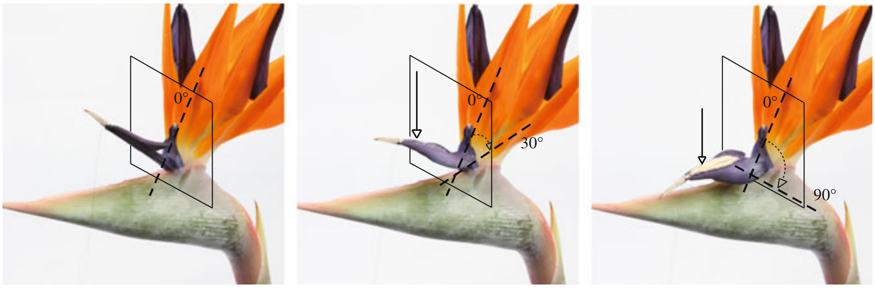

Fig. 12.2 The elastic deformation in the *Strelitzia reginae* flower. Adapted from Lienhard et al. (2011)

Fig. 12.3 Abstraction of the Flectofin® mechanism via a reduction principle. Adapted from Lienhard et al. (2009)

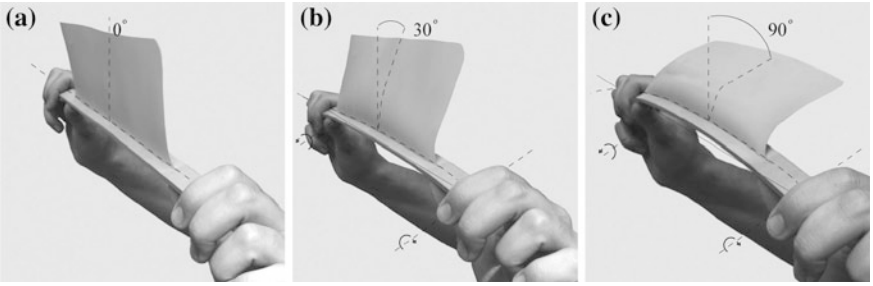

Fig. 12.4 Abstraction of the deformation principle in the flower of *S. reginae*, realised with a simple physical model. Adapted from Lienhard et al. (2011)

12.4.1.2 Optimisation of the Basic Flectofin® Principle

Further optimisation of the basic Flectofin® principle was aimed at folding two fins outward from one common element and thereby doubling the shaded area per element while hardly affecting the view. In contrast to the *S. reginae* the elastic kinetics of the double Flectofin® would need to be actuated from a common backbone. This system is shown in Fig. 12.5, with a configuration of two fins that theoretically interpenetrate (A). Therefore, they rest in position (B) where they push against each other and share a large contact area which highly increases their stability. As shown in Fig. 12.5, due to their concave curvature in their inactive state the fins bend outwards when the backbone is actuated (C–F). The leaning against each other of the fins in their 'rest position' also serves to stiffen the fins against wind deformation. As a positive side effect of the symmetrical deformation, the eccentric forces in the backbone that are induced by the bending of the fin counteract each other. This limits the torsion in the backbone and results in a more filigree profile.

It was found that the elastic kinetic system relies on perfect symmetry which is difficult to produce on a larger scale. Therefore additional geometric changes were studied to make the elastic kinetics more robust. Here, a study of the *Aldrovanda* snap-trapping mechanism (Fig. 12.6) led to the idea of using curved line folding logics to force the fins into a consistently outward folding motion. The *Aldrovanda* traps consist of two sickle-shaped lobes that are connected to a lens-shaped central portion by a curved living hinge. In the symmetry axis of the trap and in the middle of the central portion there is another distinct element to be found—a midrib that acts as the "driver" for the closing movement. When a prey (e.g., small crustaceans like water fleas) stimulates the trap by touching its sensory hairs, a sudden

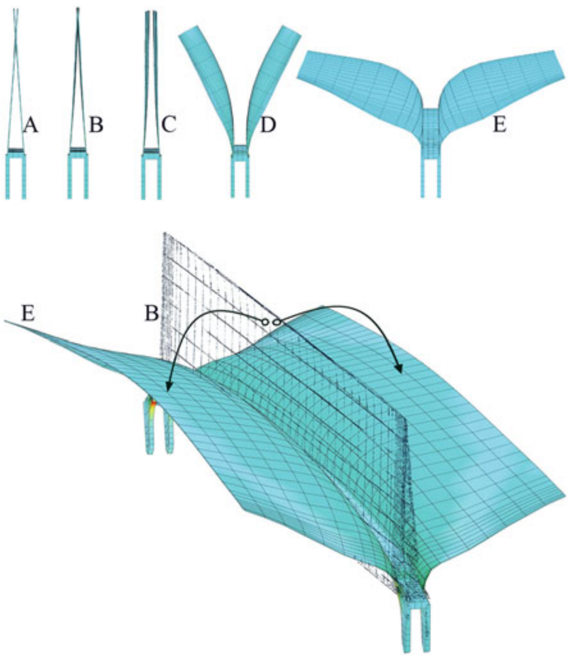

Fig. 12.5 Simulation of a double Flectofin®, **B** position of the planar fins, **B** real position of the fins pushing against each other, **E** opened fins due to bending of the backbone (Lienhard et al. 2011)

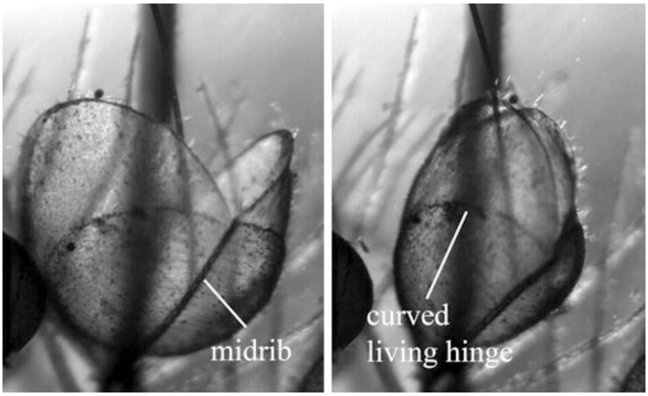

Fig. 12.6 The trap leaves of *Aldrovanda vesiculosa* in open and closed configurations

bending of the midrib leads to an instant closure of the trap lobes. From a mechanical perspective, this rapid motion results from a controlled sequence of multiple interconnected deformations. At first, the midrib starts to bend, driven by hydraulic actuation. This causes bending of the central portion, which transmits the deformation further and triggers an out-of-plane bending of the adjacent softer lobes. Similar to the Flectofin®, the mechanism is actuated by an externally induced support displacement. This translation movement causes bending in the centre surface and triggers the flapping motion of the lobes (Fig. 12.7, left)(Schleicher et al. (2010). Typically, for curved-line folding, this principle couples convex and concave surface bending, which increases in curvature as the folding proceeds. Due to the orientation of the curved-line fold, however, the lobes can rotate in the opposite direction of the Flectofin® and thus can be understood as an inverse mechanism to it. Turning the curvature around and applying it to the line between the Flectofin® fin and its backbone will consequentially force it into an outward bending motion (Fig. 12.7, right).

This Double Flectofin® is a further development of the initially proposed façade component, which has an increased shading efficiency and higher wind stability, shown in Fig. 12.8.

12.4.1.3 Architectural Application

A significant expansion for possible future applications is provided by the fact that the system functions without a straight turning axis. The geometrical flexibility of these bio-inspired compliant mechanisms renders the unique possibility to enter, for instance, the neglected market niche of shading double curved façades. Compared to traditional sun protections (e.g. blinds and louvers) whose mechanics are designed for planar and standardised facades, elastic-kinetic structures like the Flectofin® preserve their functionality even when distorted or scaled. In particular

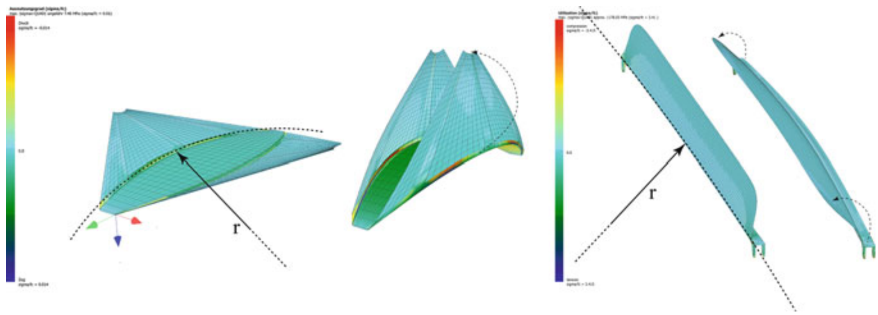

Fig. 12.7 *Left* Kinetic model of Aldrovanda's snap-trapping mechanism in FEM. Adapted from Schleicher et al. (2014). *Right curve* attachment line of the a single Flectofi® fin to its backbone

Fig. 12.8 Facade Mock-up with three Flectofin® fins with various degrees of opening

in the context of cladding double curved facades this becomes a very important and game-changing characteristic. For although the meshes of double curved façades may seem to have a smooth global appearance, they consist in fact of thousands of individual panels, which render the use of standardised shading devices practically impossible. Thus, applying a transformable shading system to this kind of facade would require the individual scaling and distortion of its components—a feature that elastic-kinetic structures can offer. Furthermore, the Flectofin® principle suits a wider range of applications, from small-scale micro-systems to large-scale architectural building components.

This concept was put to the test through the Flectofin® being the triggering inspiration for the façade of the Thematic Pavilion at the EXPO 2012 trade-fair in Yeosu, Korea, by soma-architecture and Knippers Helbig Advanced engineering. The engineering company was then commissioned with the planning and constructional design of this kinetic façade. The mechanism that should move the 108 lamellas was still unclear at the start; the central question being how one could also guarantee their functional suitability according to the expected case of a typhoon. In a first investigation, it was checked whether the Flectofin® principle could be magnified to the large scale of 108 lamellas with heights varying between 3 m and 14 m. This proved that up-scaling of the basic principle was possible, yet could not entirely fulfil the architectural intentions of the façade. Inspired by the Flectofin®, an alternative elastic kinetic mechanism was developed which is based similarly on structural failure (buckling), but does not correspond to the direct abstraction of the *S. reginae*. These further developments show the potential of such basic discoveries, in this case, the instrumentalisation of failure and deformation. In the context of architectural design, it also became clear that targeted adaptations are needed in order to be able to handle the profile of requirements in the intended field of use.

12.4.2 Textile Hybrid: M1

The Textile Hybrid M1 at La Tour de l'Architecte, France showcases the research on hybrid form- and bending-active structure systems by the Institute of Computational Design (ICD) and Institute of Building Structures and Structural Design (ITKE) with students of the University of Stuttgart and ABK Stuttgart. The scientific goal of the project was the exploration of formal and functional possibilities in highly integrated equilibrium systems of bending-active elements and multi-dimensional form-active membranes. The resulting multi-layered membrane surfaces allow not only structural integration, but also serve as a functional integration by differentiating the geometry and orientation of the membrane surfaces. The site selected for the design is a historical and structurally sensitive tower in Monthoiron, France. The tower is based on a design by Leonardo Da Vinci from the 16th century, which brought the owners to the idea of making the tower usable for exhibitions. On the basis of a spatial program, a Textile Hybrid system was developed where short-cutting of forces produced a minimisation of the loading on the tower. In the context of this project, the M1 was developed as a representative temporary pavilion.

The Textile Hybrid system was constructed with GFRP rods of diameters ranging from 3 to 24 mm in combination with textile membranes as continuous surfaces and open-weave meshes. The elastic rods gain their stiffness from active bending into curved leaf-shaped modules which are networked into a global structural system. Stress stiffening effects are activated by further deformation of the system through the integration of a pre-stressed membrane surface, and therefore create a fully Textile Hybrid system (Lienhard et al. 2013b).

12.4.2.1 Form-Finding and Construction

The system and geometry was developed by students from the University of Stuttgart through a long process of physical model building, which was later optimised through digital simulation. Aim of this process was to break free from traded structural typologies in the search for novel formal and functional possibilities in highly integrated structural systems. This process was accompanied by the consideration of natural construction principles as introduced above.

For generative studies, the spring-based modelling environment SpringFrom (Ahlquist et al. 2014) was utilised alongside exhaustive physical form-finding experiments. The computational modelling allowed for complex topologies to be developed and altered, quickly registering feedback from the prototypical physical studies. This approach was utilised for the form-finding of the secondary textile hybrid system, in particular; a series of differentiated cells providing additional structure to the primary envelope and variation to the illumination qualities of the space (Fig. 12.10). As both a design avenue and method for material specification, FEM was utilised. Here the parameters of the complex equilibrium system were explored to determine the exact geometry and evaluate the structural viability. Custom programmed methods inside the general purpose FE-Software Sofistik® allowed for great degrees of displacement to be calculated in order to form-find the beam positions. The beams were initialised as straight elements and gradually deformed into interconnected curved geometries, finally being reshaped by the inclusion of pre-stressed membrane surfaces (Fig. 12.9, right). The geometric data therein was determined initially by the physical form-finding models in defining the lengths and association points on the rods for the topology of FE beam elements (Fig. 12.9, left). Given the unrolled geometry and connection points of the rods it was possible to simulate the erection process and thereby the residual stress in a finite element based form-finding process (Fig. 12.11).

12.4.2.2 Biomimetic Approach

For the M1 project the aspect of Biomimetics is not used to look for a biological role model to find a technical solution, but define a set of strategies that influenced the entire design process. The key construction principles that influenced the design process of the M1 were:

Anisotropy: Textile materials where used on all scales; their anisotropy was used as a driving force in the design and form-finding process of the material system. For the bending rods made of pultruded GFRPs this meant that maximum material strength could be accessed, as fibres ran in the main stress direction. On a detailed level the connection points needed reinforcement by laminating fibres in the circumferential direction of the rods.

Heterogeneity: An important feature in the design was the structural integration and heterogeneity, leaving the limits of strictly categorised building structures by accumulating different load bearing strategies in an associative system. The M1

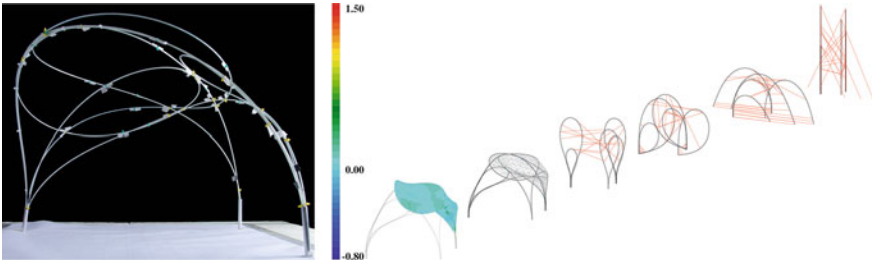

Fig. 12.9 Physical and numerical form-finding of the M1. Adapted from Lienhard et al. (2013b)

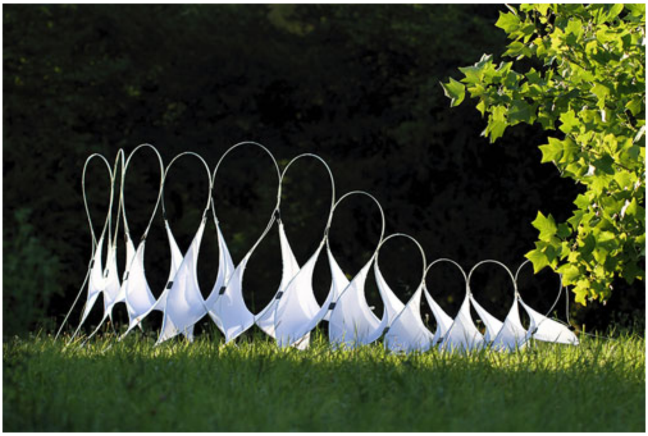

Fig. 12.10 Inner cell structure of the M1

Fig. 12.11 The textile hybrid structure M1

shows this in the way its structure freely yet continuously passes through several types of load bearing mechanisms. Thereby the system is able to adapt to changing environmental requirements without the need of changing its materiality.

Hierarchy: This system is featured on two hierarchical levels: a macro-system of interwoven bending rods that form leaf-like shapes and a meso-scale differentiated cell logic. At both scales the system logic is based upon a Textile Hybrid system in which pre-stressed membranes stabilised elastically bent rods. Repeating the macro system on a meso-scale offered the prospect of functional integration next to additional structural rigidity.

Integration: Even though, factually, the cells of the M1 do not yet serve additional functions on a physical building level, they could still be seen as placeholders for integrating such functions into small scale yet structurally relevant parts of the system. Their spatial separation of the two main membrane layers particularly offers the integration of thermal insulation and sound damping. On another level, also present in the actual M1 project, they can serve light diffusion.

This Biomimetic approach in the M1 project may show how, even though abstract in their implementation, design and construction principles found in nature can complement architectural and engineering design processes. Further examples of implementation using this approach are given in VDI Guideline 6226 (2014).

12.5 Conclusions

This chapter on bio-inspired, flexible structures introduced a general overview of elastic building materials and biomimetic abstraction techniques and showed their promising application in two case study structures.

With the Flectofin® project it was shown how direct abstraction methods may be used to extract mechanical principles from natural systems to develop novel technical engineering solutions. This example shows how nature and engineering differ in problem solving and highlights that the structures and principles identified in biological concept generators can provide innovative impulses for the development of elastic-kinetic structures beyond traditional preconceptions. The analysis of the anatomy, functional morphology and biomechanics of plants may thereby be seen as a promising approach for concept generation and optimisation in the field of architecture, building and construction.

Through the M1 project a more indirect biomimetic approach was shown. Here, the approach of studying general phenomena found in natural construction principles was successfully used to develop new structural solutions.

In general both projects show how working with biomimetics in an interdisciplinary team can help finding novel engineering solutions which are more than an optimisation of existing typologies, potentially even represent a paradigmatic change.

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